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Matrecon, Inc., Oakland, CA

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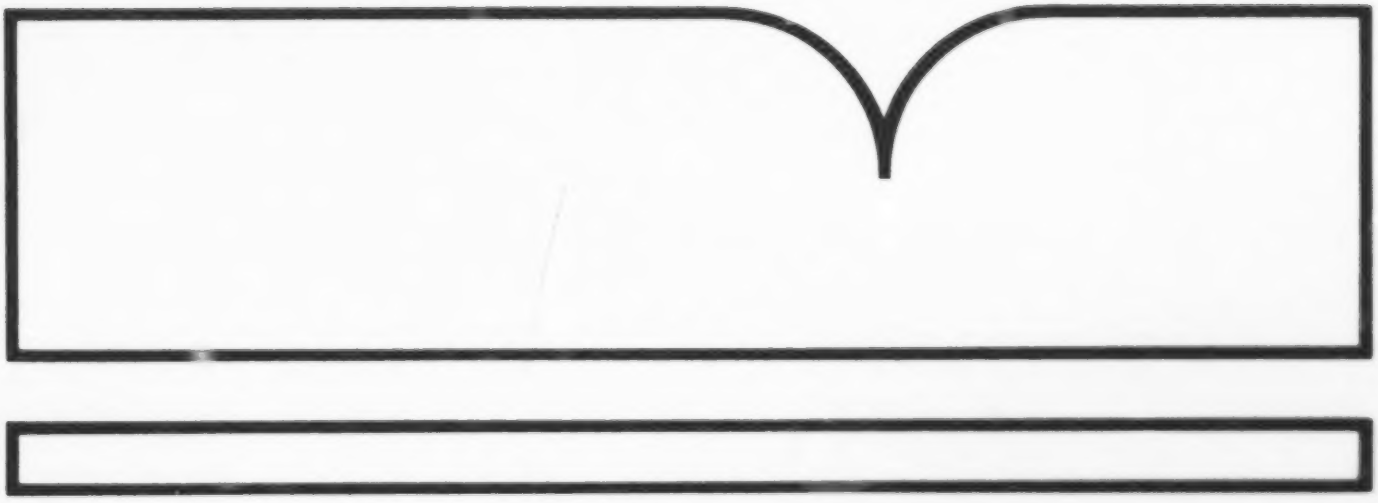

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LABORATORY TESTING OF GEOSYNTHETICS AND PLASTIC PIPE FOR DOUBLE-LINER SYSTEMS

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16. ABSTRACT

The use of polymeric products in civil engineering applications has increased dramatically over the past decade, particularly in the design and construction of waste management facilities. These materials called geosynthetics include rubber and plastic membranes, woven and non-woven textiles. Plastic pipes are also being used to collect and transmit liquids.

This paper reviews some of the basic characteristics of the polymeric materials and products that are used in the construction of double-liner systems and indicates the effects of these characteristics on field performance and laboratory testing of these products. Emphasis is placed on the testing of polymeric geomembranes and compatibility testing.

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INTRODUCTION

The use of polymeric products in civil-engineering applications has increased dramatically over the past decade, particularly in the design and construction of waste management facilities. These products include various rubber and plastic membranes that have very low permeability, woven and nonwoven textiles that have various degrees of permeability, special open constructions designed for high permeability and liquid flow, and plastic pipes (1). Except for plastic pipe, these products are called geosynthetics.

Of particular importance is the wide range of functions that polymeric products perform in double-liner systems for hazardous waste disposal facilities. These products are based on a wide range of polymers including rubbers (elastomers), plastics, fibers, and resins. With this great diversity in materials and products, an array of laboratory tests are being performed on the materials and the products to assess their quality and ability to perform in a specific application. Even for hazardous waste containment applications when a single type of material is the material of choice, thorough testing and evaluation of candidate materials are necessary due to the differences in polymers and additives used in both geosynthetics and plastic pipe.

This paper reviews some of the basic characteristics of the polymeric materials and products that are used in the construction of double-liner systems and indicates the effects of these characteristics on field performance and laboratory testing of these products. Emphasis is placed on the testing of polymeric geomembranes and compatibility testing.

POLYMERIC PRODUCTS IN A DOUBLE-LINER SYSTEM

Each construction material in a double-liner system requires testing and evaluation in terms of the specific facility and condition in which it is designed to perform. Thus, if a material will probably be exposed to a waste liquid or its vapors, it must be compatible with that particular waste stream and be able to maintain its properties over extended periods of time. Similarly, if the material is to be subjected to loads and to elevated temperatures, it must be able to function as required without failure.

The following polymeric materials of construction are being used or being suggested for use in double-liner systems (2):

Geomembranes--To provide a barrier between hazardous substances and mobile polluting substances and the groundwater; in the closing of landfills to provide a low-permeability cover barrier to prevent intrusion of rain water.

Geotextiles--To provide separation between solid wastes and drainage material and the leachate collection system or between the membrane and cover or embankment soils; to reinforce the membrane against puncture from the subgrade; to provide drainage, such as in leachate collection and leak-detection systems; to provide filtration around drainage pipes.

Drainage Nets--To provide drainage above and between liners; to provide reinforcement for side slopes and embankments.

Plastic Pipe--To provide drainage in leachate collection and leak-detection systems. Pipe is also used in the construction of monitoring ports, manholes, and system cleanouts.

Figure 1 presents a schematic of a double-liner system with indications of potential failure modes for the polymeric components used in the subsystems.

BASIC CHARACTERISTICS OF POLYMERIC MATERIALS

All of the geosynthetic materials, as well as plastic pipe, discussed in this paper are based on polymers, which are products of the chemical, plastics, rubber, and fiber industries. From the viewpoint of composition, an almost infinite range of polymeric materials can be produced. The polymeric materials used in the manufacture of geosynthetics and pipe are given in Table 1. Polymers within a type can vary according to grade and manufacturing process. In addition, considerable variation among compositions based on the same polymer is introduced by the product manufacturer through compounding with ingredients designed to enhance or develop specific characteristics. Knowledge of the composition of each geosynthetic and pipe can be important when dealing with waste liquids containing organics.

Four general types of polymeric materials are used in geosynthetics:

- Thermoplastics and resins, such as PVC and EVA.
- Crosslinked elastomers, such as neoprene and EPDM.
- Semicrystalline plastics, such as polyethylenes.
- Highly crystalline, oriented polymers, such as polypropylene and polyester fibers.

As all of these materials are polymeric, they have characteristics in common and require a broad array of tests to characterize them (3). In designing containment facilities and designing the tests needed to assess important design properties, recognition must be given to basic characteristics of polymers. Some of the important characteristics of the polymers used in products for the construction of double-liner systems are briefly discussed.

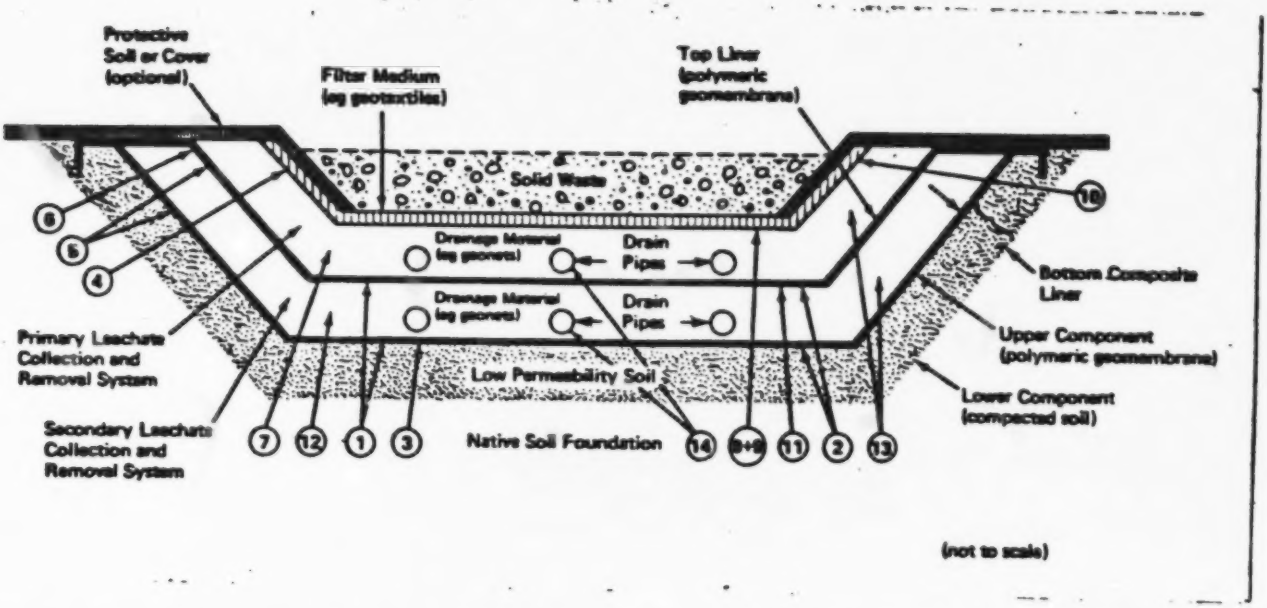

Figure 1. Schematic of a polymeric geomembrane/composite double-liner system for a landfill (2) and potential failure modes of the different components.

Potential failure modes of geomembranes:

1. Puncture due to settlement of components in leachate collection system or from irregularities in the subgrade.
2. Environmental stress-cracking of liner at bends and creases.
3. Bridging caused by localized subsidence in the subgrade.
4. Sloughing of protective soil cover due to low coefficient of friction between membrane and soils.
5. Tensile stress under load.
6. Thermal cycling.
7. Loss of properties due to waste incompatibility.

Potential failure modes of geotextiles:

8. Loss of properties due to waste incompatibility leading to reduced fluid flow.
9. Clogging or blinding of filter material by particles in the waste.
10. Tensile stress under load.

Potential failure modes of drainage nets:

11. Intrusion of membrane into the net, leading to clogging.
12. Loss of properties, leading to reduced fluid flow.
13. Collapse of the materials under waste load.

Potential failure modes of plastic pipe:

14. Collapse of pipe under load, particularly if incompatible with wastes.

TABLE 1. POLYMERS USED IN THE MANUFACTURE OF MAJOR PRODUCTS FOR THE CONSTRUCTION OF WASTE MANAGEMENT FACILITIES

Polymer	Type	Product			
		Geomembranes	Geotextiles	Geogrids and drainage nets	Pipes
Acrylonitrile butadiene styrene	Resin	...	...	...	X
Chlorinated polyethylene	Rubber	X	...	...	...
Chlorosulfonated polyethylene	Rubber	X	...	...	...
Ethylene propylene rubber	Rubber	X	...	...	...
Ethylene vinyl acetate	Resin	X	...	...	...
Neoprene (chloroprene rubber)	Rubber	X	...	...	...
Polyamide (nylon)	Fiber/resin	X[a]	X	...	...
Polybutylene	Resin	X	...	...	X
Polyester	Fiber/resin	X[a]	X	X	...
Polyester elastomer	Resin/rubber	X	...	...	...
Polyethylene:					
Linear low-density	Resin	X	...	...	...
High-density	Resin	X	...	X	X
Polypropylene	Resin	...	X	X	...
Polyurethane	Resin/rubber	X	...	...	...
Polyvinyl chloride					
Plasticized	Resin	X	...	...	...
Unplasticized	Resin	...	...	...	X

[a]Used as reinforcing fabric in geomembranes.

Polymers Vary in Modulus and in Elongation at Break

Polymeric materials range from soft foam-like materials to high modulus structural materials. Polymeric materials that are used in waste management facilities are intermediate in modulus or stiffness. However, their elongation at break ranges from 15% to as much as 1000%. Both properties are important considerations in designing geosynthetics and plastic pipe.

Polymers are Sensitive to Organic Liquids and Vapors

As the polymeric compositions used in double-liner systems are organic in nature, they are sensitive to organic liquids; they can absorb organics from waste liquids and vapors and swell or can be leached and shrink. In either case, several properties of the composition can simultaneously change and their performance characteristics can be altered. This sensitivity to organics shows the need for compatibility testing.

Polymers are Viscoelastic and Sensitive to Temperature and Rate of Deformation

All polymeric materials are viscoelastic, that is, when undergoing a deformation they show, in varying degrees, both viscous and elastic behavior. The elastic component behaves like a spring and is independent of rate of deformation. The viscous component behaves like a dashpot and is highly dependent upon the rate of deformation and upon temperature. Rubbers, such as natural rubber and some

polyurethanes, tend to have highly elastic components, whereas many of the plastics have highly viscous components. In performing tests in extension or compression, the temperature and rate of deformation become important.

Most of the polymers used in geosynthetics and pipe vary greatly in properties with temperature, even within the temperature range in which waste containment facilities operate. At low temperatures some become glassy and brittle, and at high temperatures the thermoplastic polymers become soft and plastic. These characteristics will greatly affect the applications in which a polymeric material can be used.

Due to the viscous component of polymeric compositions, the speed at which they are deformed greatly affects the magnitude of the values that are obtained, e.g., tensile or tear values. At high test speeds, modulus values generally are considerably higher; the effect on tensile strength and elongation at break values varies with the polymer. In the case of semicrystalline materials, such as HDPE, high-speed testing will not allow time for crystals to align themselves during the test, thus resulting in lower tensile at break values than those obtained at lower speeds. In service environments deformation rates can range from rapid impacts to slow creep.

Polymers Tend to Creep and Relax in Stress

Polymeric materials have a relatively high tendency to creep, that is, to increase in length or change dimensions under load or to relax in stress when placed in constant strain. This characteristic is important to long-term exposure such as would be encountered in a double-liner system. For example, in-place drainage nets and pipes are under constant load and a geomembrane placed over a protrusion is under constant stress. The absorption of organics can aggravate this tendency.

High Coefficient of Thermal Expansion

All polymeric materials have thermal coefficients approximately 10 times greater than those of metals and concrete. For soft geomembranes, this is not a major problem; however, for stiff membranes, such as the polyethylenes, changes in temperature can cause considerable deformation and flexing of a liner when exposed to normal weather and high stress in the liner when exposed to cold weather.

Importance of Thermal and Strain History

Polymeric materials tend to have "memory," that is, the deformation during processing and forming into sheets leaves residual strain in many polymers, which is why tensile and tear testing should be performed in both machine and transverse directions. Residual strain can cause shrinkage in the machine direction and expansion in the transverse direction when the sheeting is warmed.

Elongation Under Biaxial Straining

Most of the tensile and tear testing for specification purposes is performed uniaxially, which can yield high elongations. Performing the tests biaxially, that is, deforming the materials simultaneously in machine and transverse directions, yields considerably lower elongation values. This can show up in the testing of puncture and hydrostatic resistances and in actual service.

Broad Range of Permeability

The permeability of the polymeric compositions to various gases and vapors can vary over several orders of magnitude. Generally, the presence of plasticizers increases permeability and the presence of crystalline structure reduces permeability. Also of importance is the relationship between the solubility characteristics of the permeant and the polymer; the more soluble the permeant is in the geomembrane, the higher the probability of permeation.

Stress-Cracking and Static Fatigue

Polymeric materials, as with other types of materials, are subject to fracture after being under stress and strain for extended periods of time. A material under constant stress loses tensile strength and elongation at break. Semicrystalline polymeric compositions, when placed under stress in environments that affect the surface of the material, can crack or craze. This phenomenon occurs with some grades of polyethylene and polyester elastomers. The stress-cracking resistance of semicrystalline polymers that might be used in contact with waste liquids over long periods of time should be assessed.

Amorphous and Crystalline Phases in Semicrystalline Polymers

Semicrystalline polymers, such as polyethylene, contain two basic phases: 1) an amorphous phase in which the molecular structure is random, such as in a rubber; and 2) a crystalline phase in which the molecular structure is highly ordered. The crystalline phase imparts stiffness to the polymer and resists the absorption of organic species, and the amorphous phase can absorb and transmit organics. Deformation of a semicrystalline polymer results over time in molecular rearrangement in the crystalline phase. Excessive deformation results in yielding and orientation of the crystalline phase and subsequent loss in strength in the direction perpendicular to the deformation.

Highly Resistant to Degradation

With proper protection through the use of stabilizers and antidegradants, polymers used in the manufacture of geosynthetics and pipe can be highly resistant to degradation, that is, with no adverse changes in molecular structure. Polymeric compositions are still subject to loss in properties due to swelling, but polymer molecular structure remains essentially undamaged.

Polymers in polymeric compositions are also highly resistant to biodegradation; however, some compounding ingredients, such as plasticizers, may be biodegradable. Biodegradation in such cases may result in adverse changes in the properties.

Combinations of Properties in Polymeric Compositions

A given polymer will tend to have a distinct pattern of properties which can be modified somewhat by compounding. Assessing materials based upon a single property, such as tensile strength, can lead to an incorrect selection of materials because of inadequate values for other important properties, such as chemical compatibility. For this reason, a group of tests are usually performed on a material and the resulting test values are assessed as a group before a selection should be made.

PURPOSE AND TYPES OF LABORATORY TESTS

A double-lined waste management facility is a complex system, each component of which must meet performance criteria for the service life of the facility. Failure of a single component could lead to failure of the system. Due to the inaccessibility of components of double-liner systems, rational selection and evaluation of each component is of critical importance to the long-term functioning of the facility. Rigorous testing programs designed to assess the properties of these materials are an indispensable part of the design process.

Laboratory tests are performed for the following reasons:

- To assess the ability of certain materials to perform in specific field environments.
- To aid in the selection of materials for the construction of a specific facility.
- To assess durability under some extreme conditions.
- To develop data useful in the designing of containment facilities.
- To ascertain for quality assurance purposes that the materials of construction placed in the field meet design specifications.
- To identify the materials and follow changes in composition during service.
- To monitor the properties of the liner during service.

Laboratory tests designed to assess the ability of these polymeric construction materials to perform as required in the design and to meet the challenges of the field environment are needed.

The types of tests used to assess the attributes of polymeric construction materials fall into several categories. Tests of mechanical properties are most commonly used to assess the characteristics of these materials. The test values are then used in the material specifications that are incorporated into the design documents. At the present state of liner technology, the relationships between mechanical properties of particular geosynthetics as measured in the laboratory and their field performance have not been well defined. Thus, when only laboratory test data on mechanical properties are available, the designer will often rely upon his experience in the field as the basis for design judgment.

Performance tests are designed to assess the ability of one or more materials to perform under a specific set of conditions that simulate those that exist in the field. Performance tests are generally complex, usually involve many steps, and need considerable control. Such tests are beginning to evolve for geosynthetics and plastic pipe in double-liner systems. EPA Test Method 9090 for liner compatibility with a waste liquid is a performance type of test because an actual waste liquid is used as the immersion medium (4).

A major difficulty in designing performance tests of the various materials under conditions encountered in double-liner systems is the necessity of reproducing in

the tests the field conditions in which the liner system will perform. For example, they might need to include identical soils, at the correct moisture contents, wastes, and construction materials that will be used. Tests that have been used and which relate to some aspects of field peformance include:

- Permeability of geomembranes, e.g., pouch test (5).
- Frictional properties at the soil, membrane, and geotextile interface.
- Strength and elongation of geomembranes tested biaxially, e.g., hydrostatic resistance.
- Transmissivity, permittivity, and filter properties of geotextile, soil, and geogrid systems.

Most performance tests of geosynthetics and plastic pipe in waste containment applications as they exist today are in the early stages of development and require additional research in order to understand and control the test variables and to interpret the test results. At present, field verification data and long histories of use of these construction materials in waste liquid environments are meager.

Analytical tests are used to determine the composition of materials and to evaluate changes in composition over time under waste and environmental exposures (6). They include analyses for volatiles, ash content, analysis of the ash for trace metals, extractables (amount and composition), gas chromatography of extractables and by pyroprobe, differential scanning calorimetry of semicrystalline compositions, thermogravimetric analysis, and specific gravity. These tests can be used to "fingerprint" a polymeric material for quality control purposes.

The testing of the various polymeric components used or potentially used in double-liner systems are discussed in the following sections.

TESTING OF GEOMEMBRANES

The basic requirements of a geomembrane liner are low permeability to waste constituents, compatibility with the waste liquid to be contained, durability for the lifetime of the facility, and ease of construction and installation. Laboratory tests of these materials need to be selected or designed to assess these attributes. It is also desirable to be able to identify each geomembrane in order to be certain that an approved membrane is used in the final construction and to follow the effect of an exposure on a geomembrane through testing samples of the exposed liner. Table 2 presents a list of test methods that are being used in assessing the various types of polymeric geomembranes. The testing of geomembranes for use in the lining of waste disposal facilities has been discussed by Haxo (7) and in the an EPA Technical Resource Document (8). Specific test methods, including the modification of some ASTM methods, have been adopted by the National Sanitation Foundation (9).

Permeability

As the primary function of a liner is to prevent the flow of mobile liquids and other chemical species, permeability of the geomembrane to these species must

TABLE 2. APPROPRIATE OR APPLICABLE TEST METHODS FOR UNEXPOSED POLYMERIC MEMBRANES

Property	Membrane Liner Without Fabric Reinforcement			Fabric reinforced
	Thermoplastic	Crosslinked	Semicrystalline	
Analytical properties				
Volatiles	MTH-1[a]	MTH-1[a]	MTH-1[a]	MTH-1[a] (on selvage and reinforced sheeting)
Extractables	MTH-2[a]	MTH-2[a]	MTH-2[a]	MTH-2[a] (on selvage and reinforced sheeting)
Ash	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34 (on selvage)
Specific gravity	ASTM D792, Mtd A	ASTM D297, Section 15	ASTM D792, Mtd A	ASTM D792, Mtd A (on selvage)
Thermal analysis:				
Differential scanning calorimetry (DSC)	na	na	yes	na
Thermogravimetry (TGA)	yes	yes	yes	yes
Physical properties				
Thickness - total	ASTM D638	ASTM D412	ASTM D638	ASTM D751, Section 6
Coating over fabric	na	na	na	Optical Method
Tensile properties	ASTM D882, ASTM D638	ASTM D412	ASTM D638 (mod)	ASTM D751, Mtd A and B (ASTM D638 on selvage)
Tear resistance	ASTM D1004 (mod)	ASTM D624, Die C	ASTM D1004	ASTM D751, Tongue Mtd (modified)
Modulus of elasticity	na	na	ASTM D882, Mtd A	na
Hardness	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D (selvage only)
Puncture resistance	FTMS 101B, Mtd 2065	FTMS 101B, Mtd 2065	FTMS 101B, Mtd 2065	FTMS 101B, Mtd 2031 and 2065
Hydrostatic resistance	na	na	ASTM D751, Mtd A	ASTM D751, Mtd A
Seam strength:				
In shear	ASTM D882, Mtd A (mod)	ASTM D882, Mtd A (mod)	ASTM D882, Mtd A (mod)	ASTM D751, Mtd A (mod)
In peel	ASTM D413, Mach Mtd Type 1 (mod)	ASTM D413, Mach Mtd Type 1 (mod)	ASTM D413, Mach Mtd Type 1 (mod)	ASTM D413, Mach Mtd Type 1 (mod)
Ply adhesion	na	na	na	ASTM D413, Mach Mtd Type 1 ASTM D751, Sections 39-42
Environmental and aging effects				
Ozone cracking	ASTM D1149	ASTM D1149	na	ASTM D1149
Environmental stress-cracking	na	na	ASTM D1693	na
Low temperature testing	ASTM D1790	ASTM D746	ASTM D1790 ASTM D746	ASTM D2136
Tensile properties at elevated temperature	ASTM D638 (mod)	ASTM D412 (mod)	ASTM D638 (mod)	ASTM D751 Mtd B (mod)
Dimensional stability	ASTM D1204	ASTM D1204	ASTM D1204	ASTM D1204
Air-oven aging	ASTM D573 (mod)	ASTM D573 (mod)	ASTM D573 (mod)	ASTM D573 (mod)
Water vapor transmission	ASTM E96, Mtd BW	ASTM E96, Mtd BW	ASTM E96, Mtd BW	ASTM E96, Mtd BW
Water absorption	ASTM D570	ASTM D471	ASTM D570	ASTM D570
Immersion in standard liquids	ASTM D471, D543	ASTM D471	ASTM D543	ASTM D471, D543
Immersion in waste liquids	EPA 9090	EPA 9090	EPA 9090	EPA 9090
Soil burial	ASTM D3083	ASTM D3083	ASTM D3083	ASTM D3083
Outdoor exposure	ASTM D4364	ASTM D4364	ASTM D4364	ASTM D4364
Tub test	b	b	b	b

[a]See reference (8).
[b]See reference (12).
na = Not applicable.

be assessed. Transport through a geomembrane occurs on a molecular level and depends on the solubility of the permeating species and its diffusibility in the membrane. A concentration or partial pressure gradient across the membrane is the driving force for the direction and rate of transport. The species migrates through the membrane from higher to lower concentration; at a small difference in concentration, the transmission can approach zero for specific species. In contrast, soils and clays are porous and the driving force for permeation is the hydraulic head. Test methods that are available and have been used to assess the permeability of polymeric geomembranes include: 10

- ASTM D814, for determining organic vapor transmission.
- ASTM D1434, for determining gas transmission (10).
- ASTM E96, for determining moisture, vapor, and modified for organic vapor transmission (10).
- Pouch test, for determining transmission of organics in dilute solutions (5).

The permeability of geomembranes to different species can vary by orders of magnitude, depending on the composition and solubility of the migrating species in the geomembrane (10, 11). The permeation of a given species is also affected by such factors as crystallinity, filler content, density, crosslink density of the polymer, thickness of the geomembrane, temperature, and the driving force across the membrane. Also, swelling of a geomembrane during service can significantly increase its permeability to some species.

Compatibility with Wastes

The selection of a geomembrane depends on whether it is compatible with the liquid to be contained (12). A liner is compatible with a liquid if, on long exposure, its properties, e.g., permeability and mechanical properties, do not change more than reasonable amounts depending on the type of membrane. In the absence of criteria for determining the success or failure of materials under exposure to specific wastes, experience is required in interpreting changes or trends that develop over time.

EPA Test Method 9090 was designed to assess the compatibility of geomembranes and waste liquids by simulating some of the conditions a geomembrane would encounter as an unstretched coupon in representative samples of the waste liquids or leachates to be contained (4). In this test, liner samples in slab form are immersed for up to four months at 23 and 50°C in the waste liquid. Testing is performed on the unexposed membranes for baseline data and on samples exposed to the waste liquids for 30, 60, 90, and 120 days to assess the effects of immersion. Testing required by the method includes determination of tensile properties, tear resistance, puncture resistance, and hardness. In addition, the weight and dimensions of the individual test slabs before and after exposure are measured.

A major challenge in conducting the 9090 test is maintaining, as closely as possible, the composition of the waste liquid in the test cells for the duration of the tests as it would be encountered in the "real world." Changes in the concentration of dissolved constituents in a waste liquid can occur because of loss

of volatiles from the immersion cell or absorption by the geomembrane under test. Consequently, if the leachate contains volatile organics, it is necessary to seal the cells in which samples are immersed and to test the samples promptly after removal. Also, though not required by the 9090 test method, it may be necessary to change the liquid monthly at the time the sample is removed in order to maintain a constant concentration of the organics. Table 3 illustrates partitioning of organics between water and HDPE and the degree that organics are absorbed by the HDPE sample immersed in an aqueous solution of 10 organics in a 9090-type test. The acetone and methyl ethyl ketone preferentially partitioned to water, whereas the other 8 organics partitioned to the HDPE.

TABLE 3. PARTITIONING OF ORGANIC SOLVENTS BETWEEN WATER AND AN HDPE MEMBRANE AFTER 30 DAYS OF EXPOSURE IN A 23°C AQUEOUS SOLUTION SPIKED WITH TEN ORGANICS

Organic in spike	Initial spike[a] (mg/g)	Concentration in water at 30 days[b] (mg/g)	Concentration in HDPE membrane at 30 days[c] (mg/g)	Ratio[d] C_{PE}/C_w
Acetone	0.198	[e]	0.000	...
Methyl ethyl ketone	0.201	0.201	0.000	<0.002
Trichloroethane	0.335	0.000	1.42	>1400
Benzene	0.220	0.018	0.46	26
Trichloroethylene	0.366	0.032	1.58	49
Toluene	0.217	0.031	2.63	85
m-Xylene	0.072	0.0089	1.46	164
o-Xylene	0.073	0.0034	1.17	344
Tributyl phosphate	0.243	0.016	0.32	20
Di(ethyl hexyl) phthalate	0.247	0.0057	0.11	19

[a]Based upon the solubility of individual organic in water.
[b]Concentration determined by gas chromatography.
[c]Concentration determined by headspace gas chromatography.
[d]Ratio of concentration of the organic in the HDPE membrane divided by the concentration in water.
[e]Not detectable by the gas chromatograph.

Partial results of a 9090 test of an 80-mil HDPE geomembrane in a waste liquid containing organics are presented in Table 4. The test was conducted in a manner to prevent loss of volatiles and to maintain concentration of the organic constituents in the waste liquid. Determination of the volatiles and extractables of the exposed sample improves the interpretation of the results. The current EPA Test Method 9090 does not include testing of seams and the effect of strain on a geomembrane (4). Inclusion of such testing would enhance the method and make conclusions regarding compatibility more reliable.

Durability

A polymeric geomembrane used to line a hazardous waste storage and disposal facility must maintain its integrity and performance characteristics over the designed life of the facility. Liners must resist physical damage during installation and service; the integrity of the seams must be maintained so that cracks, breaks, tears, and other holes do not develop in the liner system. Fabric

reinforcement is used with CSPE, CPE, and other polymers to increase durability, particularly during installation. Ultimately, the service life of a given liner will depend on the intrinsic durability of the material and on the conditions under which it is exposed during service (13). 12

TABLE 4. PARTIAL RESULTS OF COMPATIBILITY TESTING OF AN 80-MIL HDPE GEOMEMBRANE ON IMMERSION IN A LEACHATE[a] AT 23°C

Original Values of Properties and Percent Retention of Values after One, Two, Three, and Four Months of Immersion at 23°C

Property	Direction of test	Initial values	Exposure time, months 1	2	3	4
Analytical properties			Test values			
Volatiles, %		0.1	2.64	2.89	3.26	3.13
Extractables, %		≤0.6	0.90	1.43	1.40	[b]
Dimensional properties			Percent change			
Weight[c]		...	+5.5	+6.0	+6.0	+5.9
Physical properties			Percent retention			
Tensile at yield	Machine	18.5 MPa	90	88	89	89
	Transverse	18.8 MPa	90	92	90	91
Tensile at break	Machine	29.9 MPa	89	91	102	93
	Transverse	30.7 MPa	91	82	97	83
Elongation at break	Machine	835%	98	99	105	98
	Transverse	830%	100	93	96	93
Stress at 100% elongation	Machine	13.0 MPa	90	89	90	90
	Transverse	12.7 MPa	91	93	92	91
Modulus of elasticity[d]	Machine	855 MPa	73	[e]	60	62
	Transverse	811 MPa	75	69	63	61
Tear strength	Machine	148 kN/m	89	93	89	88
	Transverse	148 kN/m	86	91	89	88
Puncture resistance			Test values			
Maximum stress, normalized for 100-mil sheeting, N		717	725	669	657	672
Retention of stress for 100-mil sheeting, %		100	101	93	92	94
Elongation at puncture, mm		15.5	19.3	18.0	17.0	18.3
Hardness, Duro D points			Change in points			
5-second reading		63	-8	-8	-9	-7

[a]Leachate was changed monthly.
[b]Not measured.
[c]Weight gain may be due to swell and/or encrustation of sample.
[d]Measured using 12.7 mm x 203-mm strip specimens with an initial jaw separation of 10 mm and an initial strain rate of 0.1 mm/mm min. Using a specimen with a 250-mm gage length, recommended as standard in ASTM D882-83, would result in somewhat higher values.
[e]Unreliable result.

Laboratory tests for assessing the durability of geomembranes under different environmental conditions range from chemical analyses to tests of mechanical properties (e.g., tensile properties, tear resistance, puncture resistance, and impact resistance) under various exposures in aggressive environments, such as exposure to high and low temperatures, to ozone while under strain, to ultraviolet light, to stress and strain for extended periods of time, and to the combined effects of chemicals and stress. Specific tests to assess these properties are listed in Table 2 for different types of geomembranes.

Important in long-term service of a polymeric geomembrane liner is its ability to resist the effects of creep and biaxial strain that will occur when it is under load and rests on a nonplanar or irregular surface, such as exists at the bottom of a containment facility. Cracks and breaks can occur in a polymeric geomembrane at significantly lower stress values than are encountered in the simple uniaxial tensile test.

As with compatibility testing, maximum changes in properties that can take place without affecting overall performance have not been established. Nevertheless, laboratory testing of several properties can yield data indicative of durability.

Seamability and Quality of Seams

In constructing a large continuous leakproof liner from prefabricated sheeting, pieces of sheeting must be seamed. Sheetings of a roll width less than 1.8 m are seamed together in a factory to form panels which are brought to the field and seamed. Sheeting of a roll width greater than 6 m is brought to the field in rolls which are then seamed. In either case, the geomembrane must be seamable and yield reliable seams that are mechanically sound and can withstand exposure to waste liquids for extended periods of time. Thermoplastic materials which can melt or which can be dissolved in a solvent yield seams that can be monolithic and/or homogeneous, i.e., the interface between the layers has been eliminated. This contrasts to sheetings which are seamed with adhesives of a composition different from the parent material. Seams are tested in both peel and shear modes in accordance with methods given in Table 2. In addition, static tests can be run in peel and shear by dead-weight loading. All of these tests can be performed at elevated temperatures, after various aging periods, and after immersion in solvents or in waste liquids as part of EPA Test Method 9090.

Various measurements and observations can be made to assess the quality of the seams. In making an assessment, it is important not only to know the force required to break seams, but also to know the durability of the seam and the manner in which a test specimen of the seam breaks. The quality of a seam can be assessed by the following observations:

- Locus of break--a break in the parent material is desirable, such as a "film tearing bond." Failure at the interface between bonded surfaces is undesirable as it may be indicative of inadequate retention of adhesion on long exposure.

- Time to break when tested under tensile load in the static mode.

- Effects of temperature and other exposures on the magnitude or locus of break.

These observations can be used in setting specifications for seam quality. Laboratory tests should be performed on samples of seams cut from liners installed in the field as part of quality assurance.

Fingerprinting of Geomembranes

Because of the wide range of polymeric geomembranes that may be encountered, analysis and fingerprinting can be useful. For example, the analysis and fingerprinting of a polymeric geomembrane liner that has been tested for compatibility with a given waste liquid in accordance with EPA Test Method 9090 can be used at the time of liner installation for the following purposes:

- As a means of characterizing and identifying the specific sheeting.
- As a baseline for monitoring the effects of exposure on the liner.
- To determine which constituents of the waste liquid were absorbed during the 9090 test and thus could affect the chemical compatibility of the waste and liner in service.

Specific analyses that may be used for fingerprinting are suggested by Haxo (6). Table 2 lists specific test methods for many of these analyses.

TESTING OF GEOTEXTILES

The tests for characterizing geotextiles that have not been exposed to wastes are fully described by Koerner (14). Also, ASTM Committee D35 is developing specific test methods which can characterize the properties associated with the respective functions. Currently used test methods are:

Property	Test method number
Thickness	ASTM D1777[a]
Mass/unit area	ASTM D3776-84
Percent open area	CWO 22125-86
Permittivity	ASTM D4491
Equivalent opening size	CWO 02215
Puncture	ASTM D3787 (modified)
Burst strength	ASTM D3786
Grab tensile/elongation (wide-width strip)	ASTM D1682[b]
Ultraviolet resistance	ASTM D4355[c]
Transmissivity	ASTM D35 Committee Draft, Designation 03.84.02

[a] 2 kPa loading.
[b] Section 16 (Grab test G) using 100 mm x 200-mm sample, 75-mm gauge length, 25-mm wide x 50-mm long grip, strain rate 305 mm/minute, using a constant rate of extension tester.
[c] 500 hours.

For assessing geotextiles for use in waste containment applications, exposure to waste liquid for four months under EPA Test Method 9090 conditions is suggested. The laboratory performance testing of geotextiles in waste liquids under load poses a problem due to the size of the test specimens and the handling of large amounts

of waste liquids. In our laboratory we have performed compatibility testing of 75 mm x 150-mm geotextile specimens in accordance with ASTM D751 by the grab method. Wet specimens were tested throughout. The unexposed specimens were first immersed in water and then tested. The exposed specimens were dewatered with a roller and then wrapped in a thin polyethylene film and tested. As the elongation properties of the film exceeded that of the fabric, it did not break; thus, the waste liquid was contained.

Performance testing of geotextile/soil systems to determine filter characteristics are reported (15, 16). Martin et al, also performed tests on drainage material/soil systems to study the effects of overburden pressures on transmissivity of geotextiles (17). Raumann conducted similar tests on geogrids (18). Performance tests have also been conducted on geomembrane/geotextile/soil systems to evaluate the frictional coefficient at the material interfaces (14).

TESTING OF DRAINAGE NETS

This group of geosynthetics, which includes geogrids, geonets, and a variety of open constructions, are based primarily on polyethylenes and polypropylenes. As such, some of their attributes are similar to those of polyethylene geomembranes. Geonets that are used for drainage in double-liner systems must maintain their drainage capability over extended periods of time. As these materials are polymeric, they are subject to creep and compression under loads, which will tend to reduce their transmissivity. The polymeric geogrid probably will absorb organic constituents from the waste liquid, which will cause it to soften and lose compressive strength and result in greater creep and further loss of transmissivity. If the lateral mechanical stability decreases, the three-dimensional structure of the net could collapse and lose drainage capacity.

A test that would be indicative of the performance of the geogrid as a drainage medium is to place the geogrid between two stiff liners or plates while in contact with the waste liquid and under load, during which time the transmissivity is measured. It would be expected that the geonet would compress and creep with time. Reduction in transmissivity would be expected, but the magnitude would vary with the material, temperature, load, and chemical absorption; however, no test of this type has yet been developed.

A modified test procedure would involve testing samples of geonet for transmissivity after they have been exposed to a waste liquid. A load that corresponds in magnitude to service conditions would be applied and the transmissivity determined. This procedure would require that the load be applied for a sufficient length of time to allow for creep and compression of the tested sample. If water instead of waste liquid is used to determine transmissivity, some of the organics in the geogrid may leach out and cause changes in the properties of the geonet.

An alternate test procedure which we have followed to measure compatibility of geonets with waste liquids is to immerse samples of geonets for up to four months in a manner similar to that used for geomembranes, and measure such properties as tensile and compression modulus as a function of exposure time. Weight changes, volatiles, and extractables are also measured. Test results are treated similarly to those obtained on geomembranes.

A wide variety of test methods for characterizing plastic pipe has been published by ASTM, the Plastic Pipe Institute, the Gas Research Institute, and the National Sanitation Foundation. Due to their good chemical resistance, plastic pipes have found considerable use in the handling of chemicals. However, the resistance can vary considerably from polymer to polymer. In waste containment facilities, PVC and HDPE pipes are used predominately. Nevertheless, pipes have collapsed due to organic solvent absorption and softening of the pipe.

Inasmuch as the leachate collection and leak-detection systems of double liner systems must function for extended periods of time, it is desirable to assess the compatibility of the pipe with the waste liquid. This can be done by exposing sections of pipe in waste liquid under conditions similar to those used in the EPA 9090 test and testing the sections after exposure in accordance with a method selected from ASTM D2412. The size of the pipe, e.g., 150 mm in diameter, and the need for replication may require large tanks and a considerable amount of waste liquid. The relatively large mass of the pipe could absorb considerable portions of the organic constituents in the liquid, resulting in a reduction of their concentrations and the need to replace the waste liquid.

In an alternate procedure which we have conducted, the pipe is tested for tensile properties parallel to the length of the pipe and for compressive modulus of a ring cut through the cross section. In this procedure, two types of specimens cut from the pipe are exposed and tested: cross-sectional rings 25 mm in length and longitudinal strips cut radially and machined to the proper thickness. The strips are tested for weight change, extractables and volatiles, tensile strength, elongation, and modulus of elasticity before and after immersion as in EPA Test Method 9090. The rings are tested in compression before and after exposure to the waste liquid to measure changes in modulus. Also measured are weight and hardness to determine changes in these properties.

DISCUSSION

As yet, maximum changes in properties which correlate with serviceability limits have not been established. Inasmuch as the effects of environmental exposures vary with the polymer, each material would have a separate set of maxima. Expert systems are being evolved by the U.S. Environmental Protection Agency to aid in assessing compatibility of liners and waste liquids (19). However, feedback from the field performance of liners and from testing liners that have been in service is needed to established correlation between field performance and laboratory testing.

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